

Laboratory demonstration of the Sub-microradian ATP Subsystem for deep space optical communications

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/Jet Propulsion Laboratory

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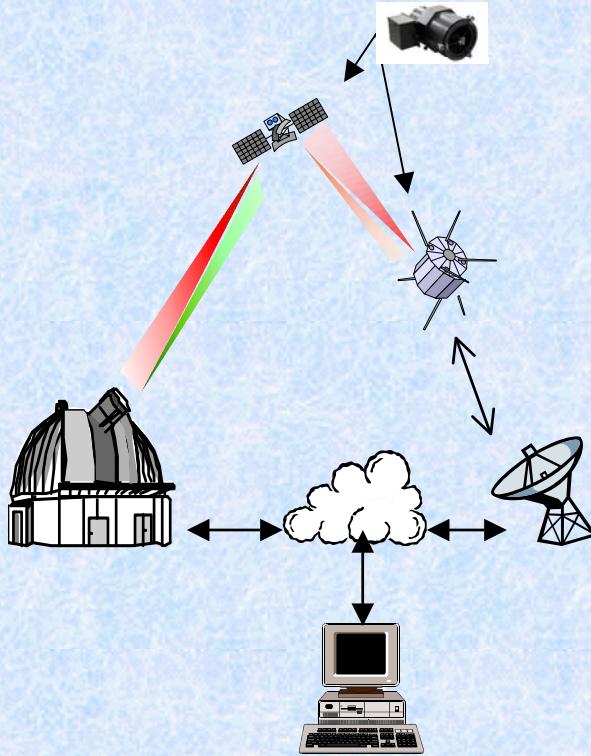
- **Introduction**
 - Innovation and Uniqueness; Benefits to NASA
 - Sub-microradian pointing systems for deep space optical communication links
- **Sub-microradian ATP Subsystem**
 - Design drivers; architecture; overall challenges; trades
- **Laboratory Progress**
 - Integrated all components
 - RAWCCD Camera testing
 - Centroiding Accuracy
 - Tracking Accuracy
 - Performance: Estimated vs. Measured
- **Summary**

Introduction

- **Technology Innovation:**
 - Development and integration of advanced components/subsystems, which improve random and system noise and dynamic range
 - system-level improvements in ATP algorithms and architectures to achieve ATP pointing accuracy to the sub-microradian level
 - Unified ATP architecture
- **Comparison with the State-of-the-Art:**
 - Hubble Telescope; Pointing accuracy ~ 35 nrad
 - Starlight; ~ 0.5 urad RMS relative pointing control
- **Uniqueness of this technology:**
 - absolute and accurate sub-microradian pointing control from anywhere within the solar system and beyond
 - enables 6-10 times improvement in data-rate delivery from deep space to Earth

Introduction

- **Uniqueness of NASA need:**
 - Precise pointing of optical communication signals yields stable links, with low fade probability and increased link margins. This enables delivery of high volumes of science data such as hyper-spectral imaging and laser altimetry from spacecraft to ground.



- **Customer Relevance and Benefits to NASA:**

Optical Communication technology may be utilized in the following communication links:

- Deep space to ground (SSE, HEDS), eg:
 - 1 Mbps from Mars, 100 kbps from Europa
- Intersatellite links, (ESE) eg:
 - Multi-Gbps LEO-LEO/GEO
- Earth orbiting to ground (HEDS, ESE), eg:
 - 2.5 Gbps from ISS
- Networking formation flying spacecraft (SSE)

Sub-microradian ATP System

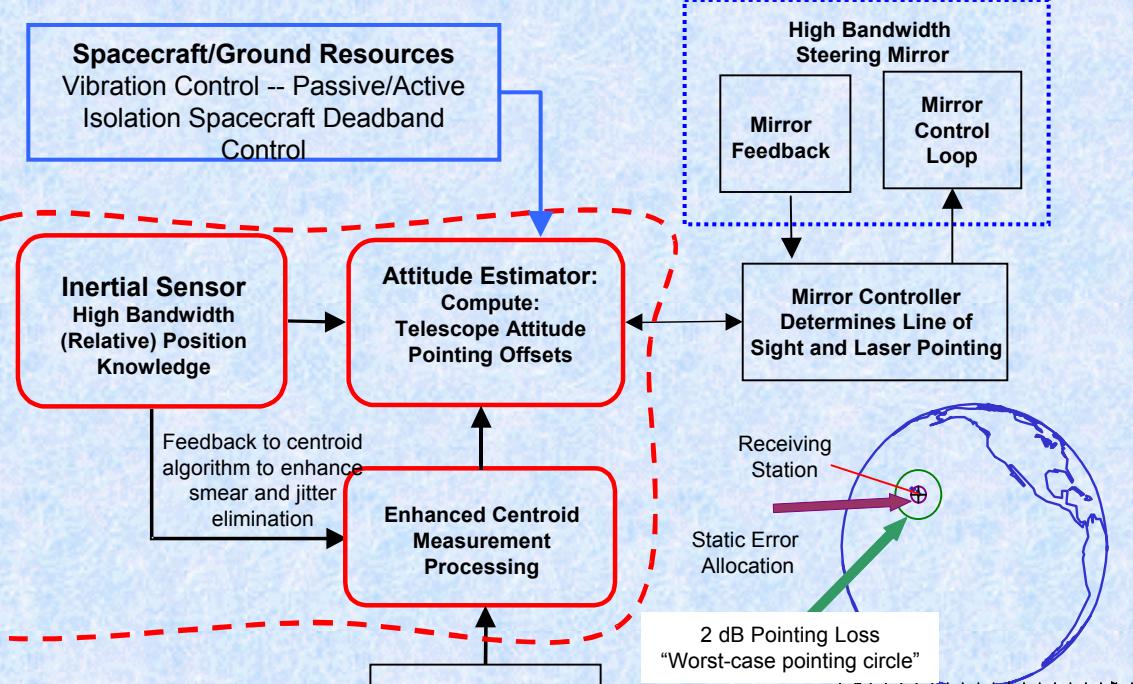
Deep Space Beacon Options

	Requirement	Comment
(A) Laser Beacon	Requires high-power uplink signal. Requires spacecraft attitude for tracking.	Only applicable at close (<1 AU) distances. Range can be extended with inertial sensors.
(B) Extended Image	Requires high Earth signal. Albedo variations cause center of brightness (COB) shifts. Either calibrate or live with offset error if possible.	At close distances, edge tracking can be used to provide updates, or use defocused downlink laser for degraded accuracy.
(C) Star Trackers	At 0 phase and 1 AU, Earth has magnitude - 3.8. Requires stars to be in FOV. Requires inertial sensors.	Signal varies with phase angle/distance ~1,600x worse at Pluto. Works with low signals. Does not require spacecraft attitude for track.
	Pointing based on J2000 coordinates/ attitude.	Track signal not a function of distance.

Generic Deep Space ATP Architecture

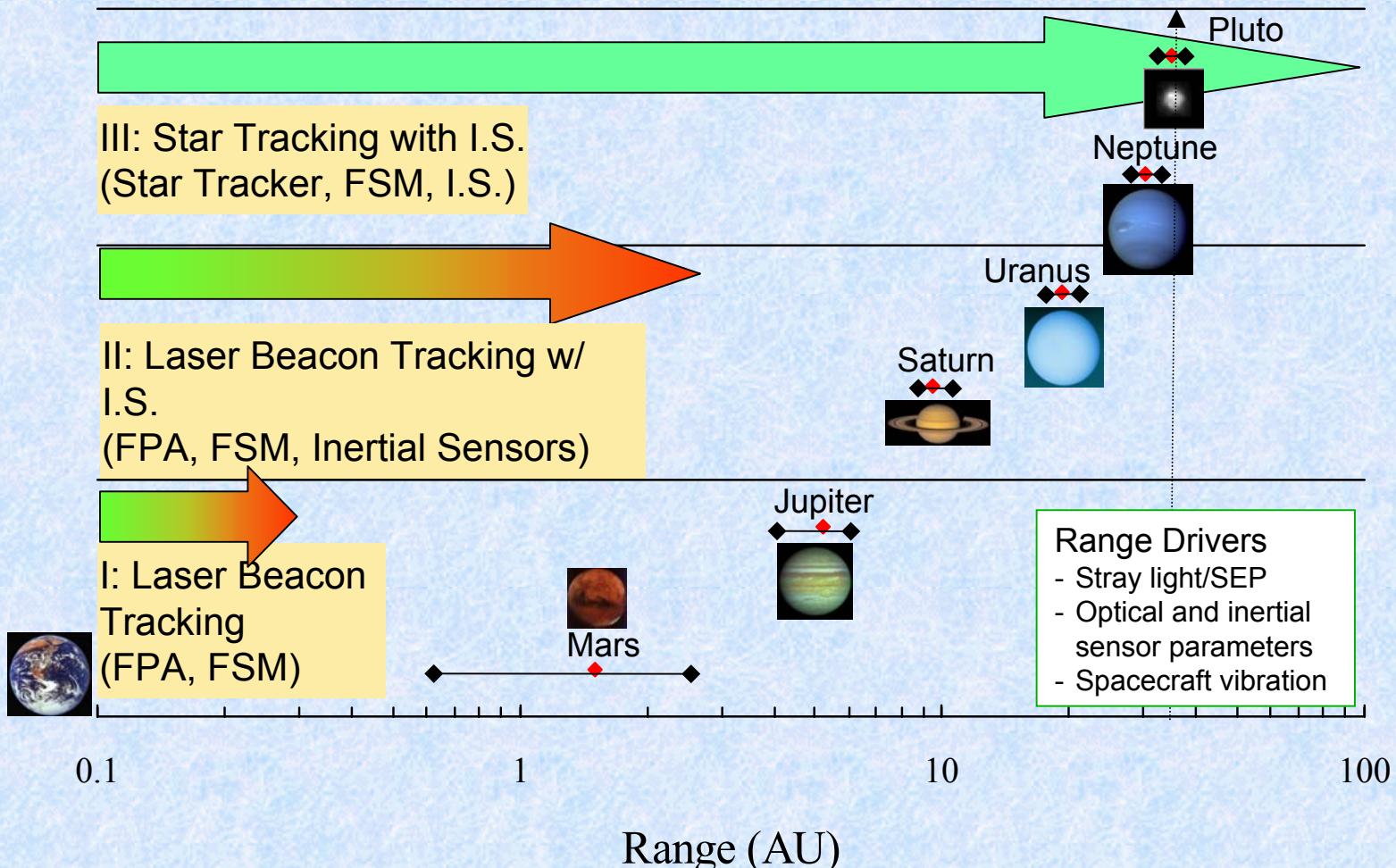
Sub-microradian ATP System

Unified Deep Space ATP Architecture



Sub-microradian ATP System

- Developed and analyzed ATP implementation approaches



Sub-microradian ATP System

- Developed and analyzed ATP implementation approaches
- FPA NEA = 0.3 μ rad**

FPA Specs

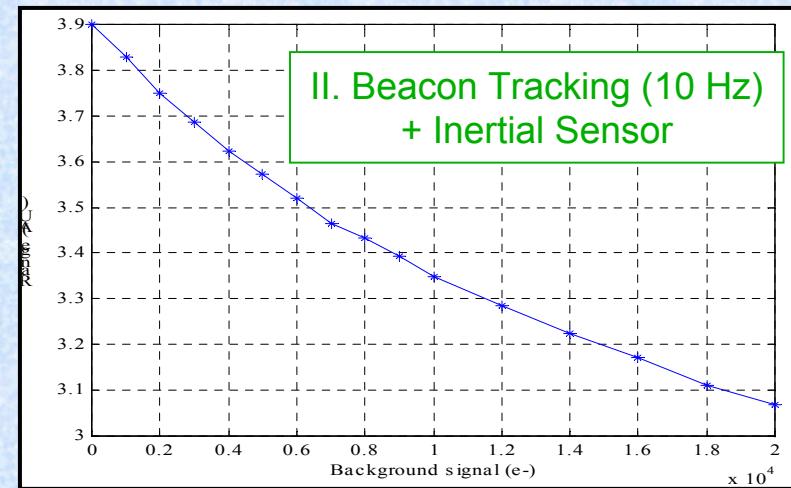
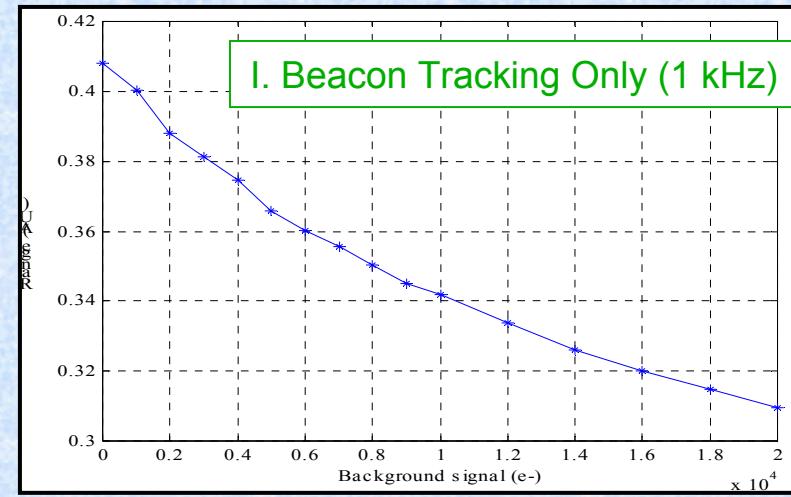
Update Rate	1 kHz, 10 Hz
Minimum Number of Photons	16,000
Read Noise	10 e-
Centroid Window	7 x 7
Dark Current	200 e-/sec
ADC Resolution	12 bits

Assumptions

Beacon Power	720 W
Wavelength	532 nm
Beacon Divergence	20 μ rad
Background Light	0 to 20 ke-
Loss (Atmosphere, Optical Efficiency, Other)	7 dB
Quantum Efficiency of CCD	50%
Aperture Size of Transmitter	30 cm

Range Limit

Beacon Tracking	0.3 to 0.4 AU
Beacon-Inertial Sensor Tracking	3.1 to 3.9 AU
Star-Inertial Sensor Tracking	None



Sub-microradian ATP System

- Developed and analyzed ATP implementation approaches

I: Laser Beacon Tracking

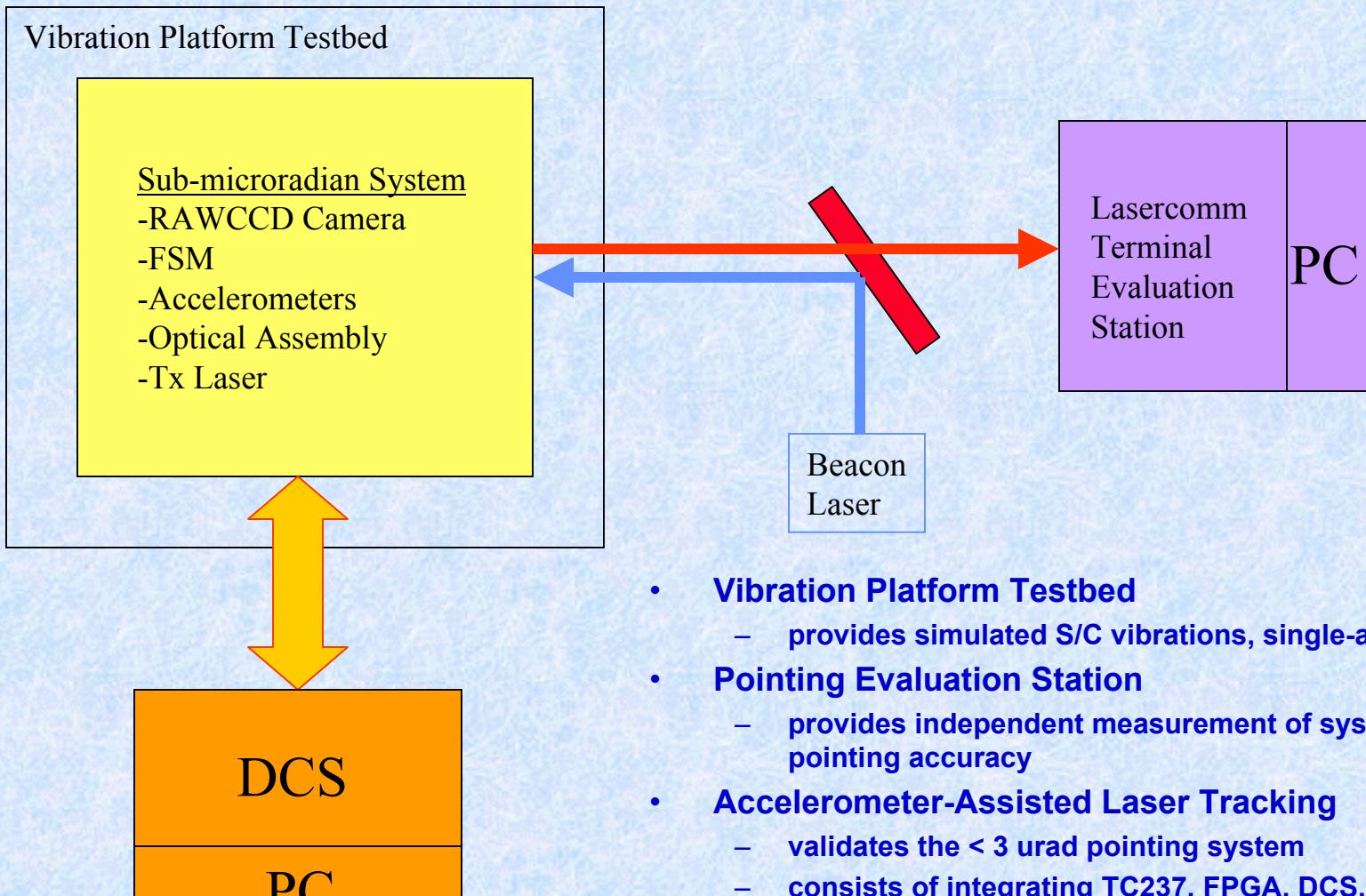
Pros	Cons
<ul style="list-style-type: none"> • Simple components • Requires little optical alignment • Works well at close ranges 	<ul style="list-style-type: none"> • Requires beacon station availability • Beacon power fades with distance • Requires high update rate for vibration rejection • Point-ahead angle compensation requires spacecraft attitude knowledge

II: Laser Beacon Tracking with I.S.

Pros	Cons
<ul style="list-style-type: none"> • Reduces optical sensor update rate • Simple components • Requires little optical alignment • Works well at close ranges • Extends link range 	<ul style="list-style-type: none"> • Needs high bandwidth inertial sensors • Requires beacon station availability • Beacon power fades with distance • Point-ahead angle compensation requires spacecraft attitude knowledge

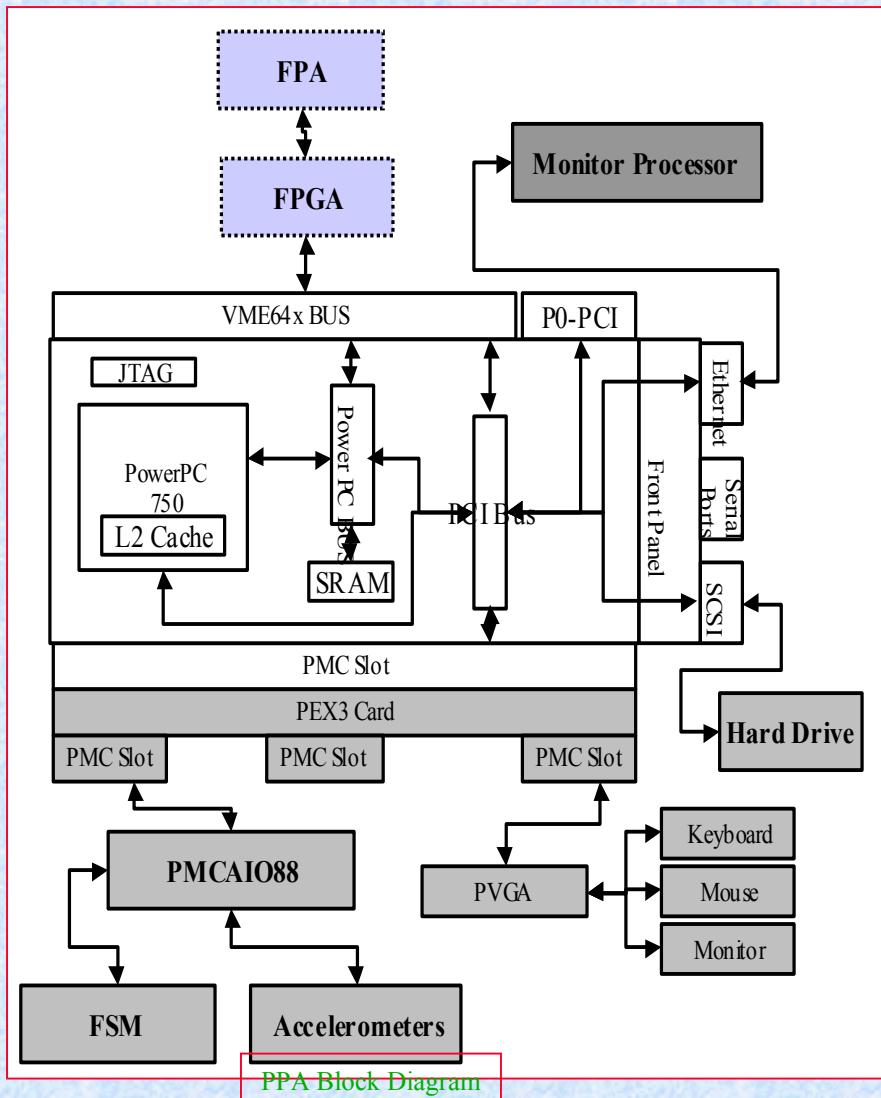
III: Star Tracking with I.S.

Pros	Cons
<ul style="list-style-type: none"> • Extends link range beyond Pluto • Does not require laser beacon • Design independent of SPE angle • Pointing accuracy does not depend on range. Angular accuracy improves with increasing range 	<ul style="list-style-type: none"> • Needs high-bandwidth inertial sensors • Star tracker accuracy depends on star availability • Requires alignment between telescopes • Extremely close ranges require better receiver position knowledge accuracy • Requires more components

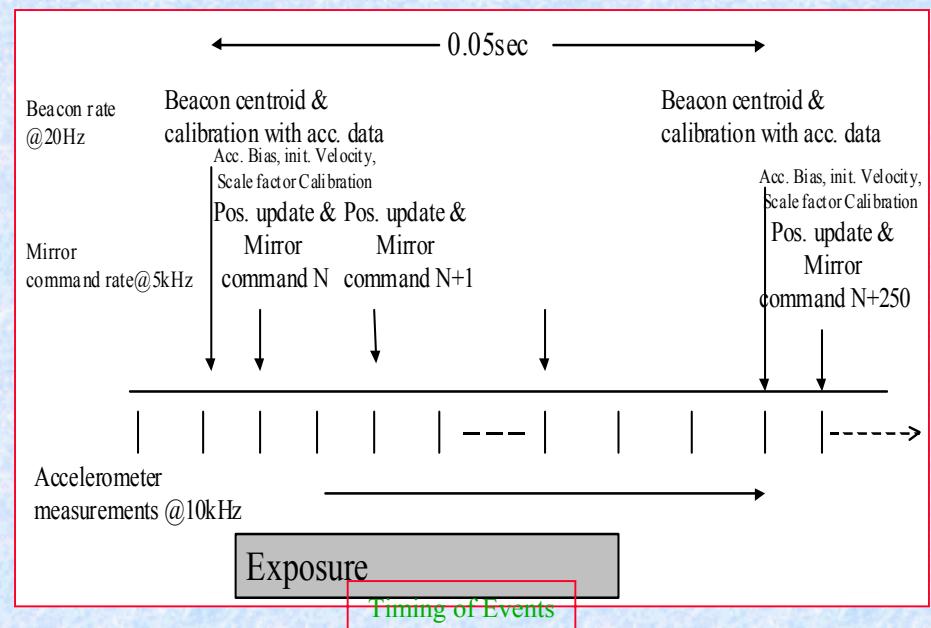


Digital Control System

Laboratory Demonstration Progress



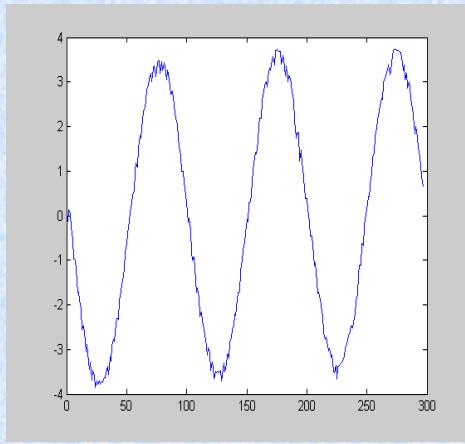
	Legacy System (benchmark)	Upgrade (estimate)
Process Step	Time (S)	Time (S)
Frame Readout	294.3×10^{-6}	$125-50 \times 10^{-6}$
Process Frame	362.8×10^{-6}	$45-30 \times 10^{-6}$
Mirror Update	31.5×10^{-6}	$30-20 \times 10^{-6}$
Total	688.9×10^{-6}	$200-100 \times 10^{-6}$
Max Command Rate	1.45 kHz	5-10 kHz



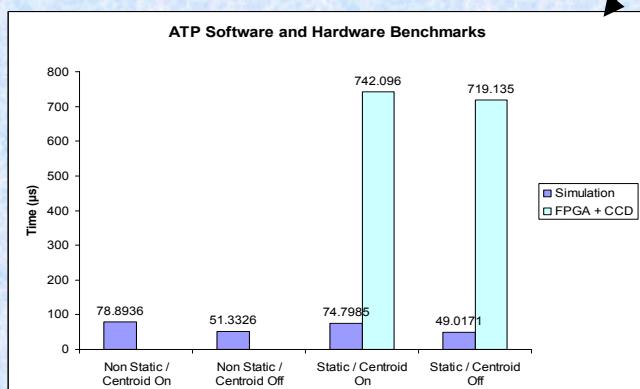
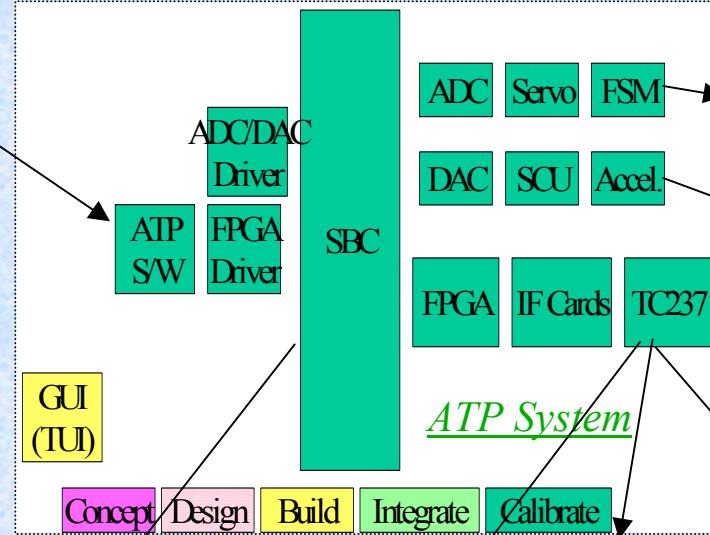
Integration of ATP Subsystem

Laboratory Demonstration Progress

Completed build, test and integration of all components of the ATP system.



X Centroid Position in pixels
with a sinusoidal input



ATP S/W & H/W Timing Benchmark

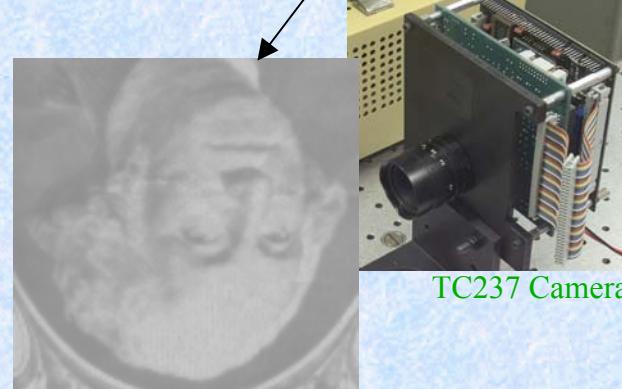
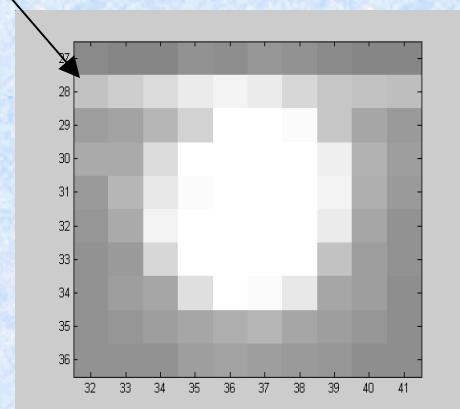


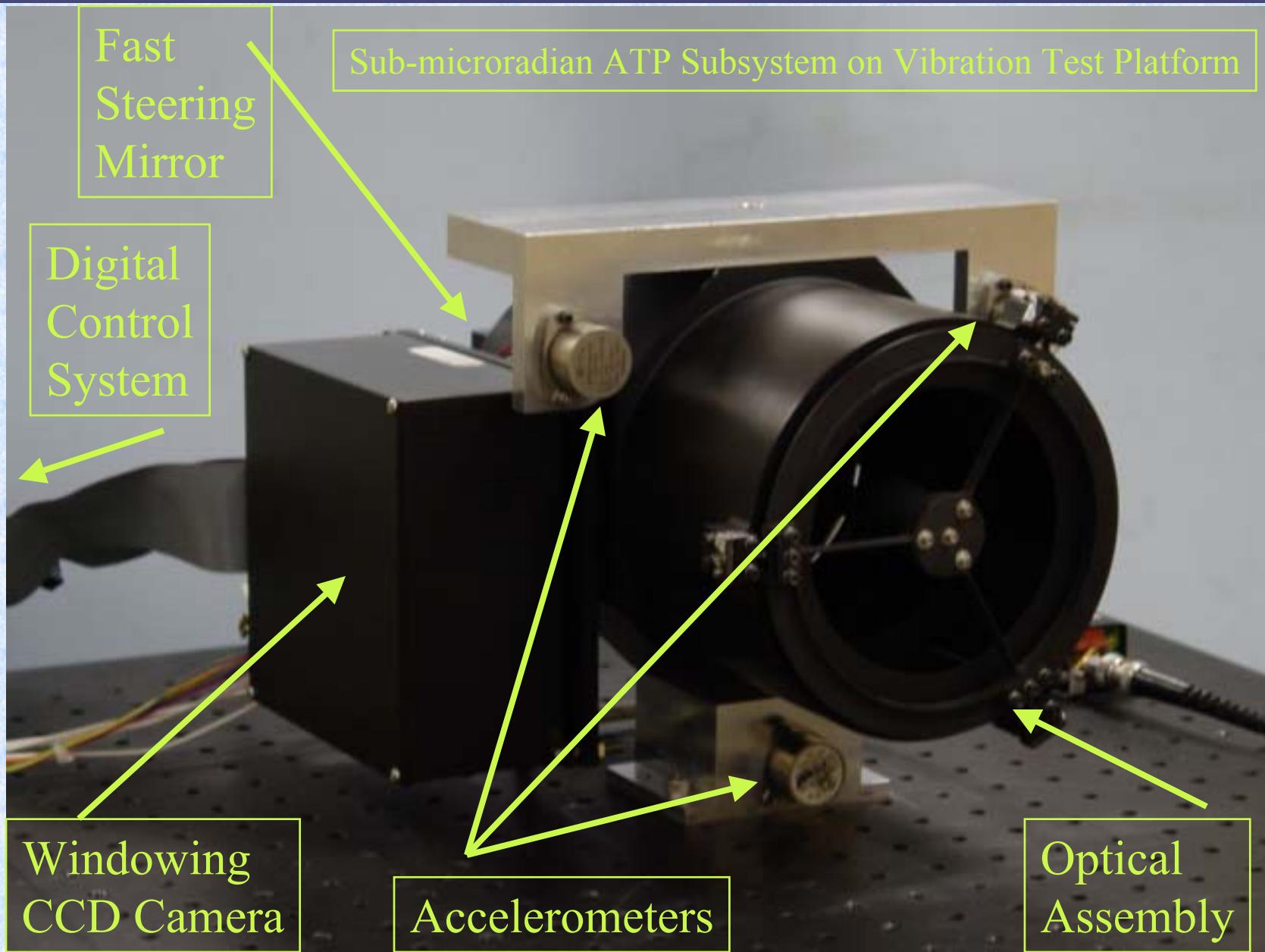
Image on TC237 Camera



Beacon Spot on TC237 Camera

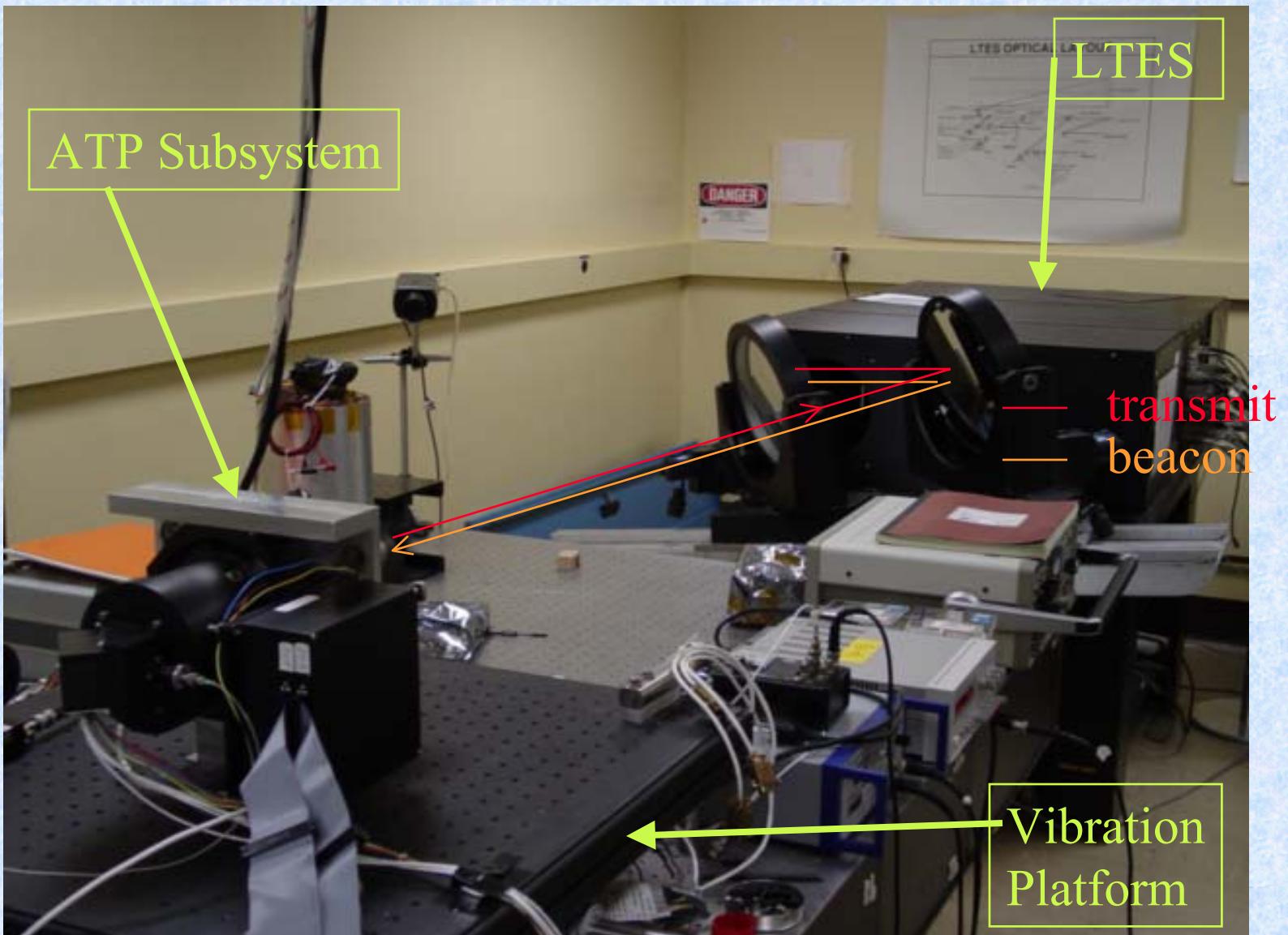
Sub-microradian ATP Subsystem

Laboratory Demonstration Progress



Lab Test Set-up

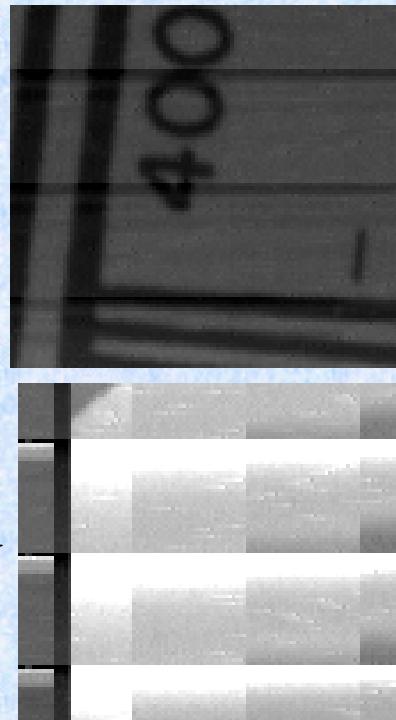
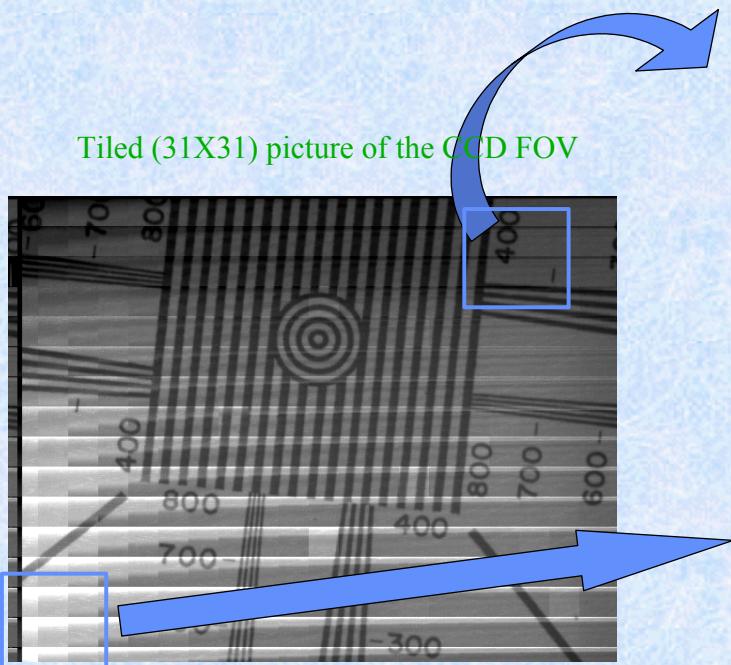
Laboratory Demonstration Progress



Laboratory Demonstration Progress

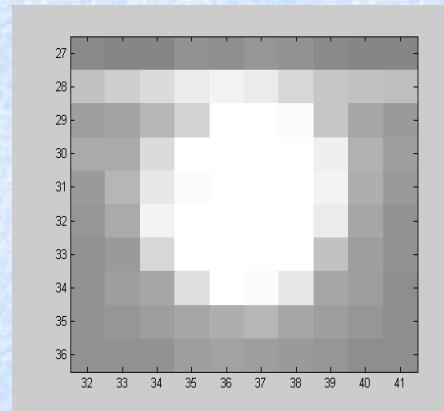
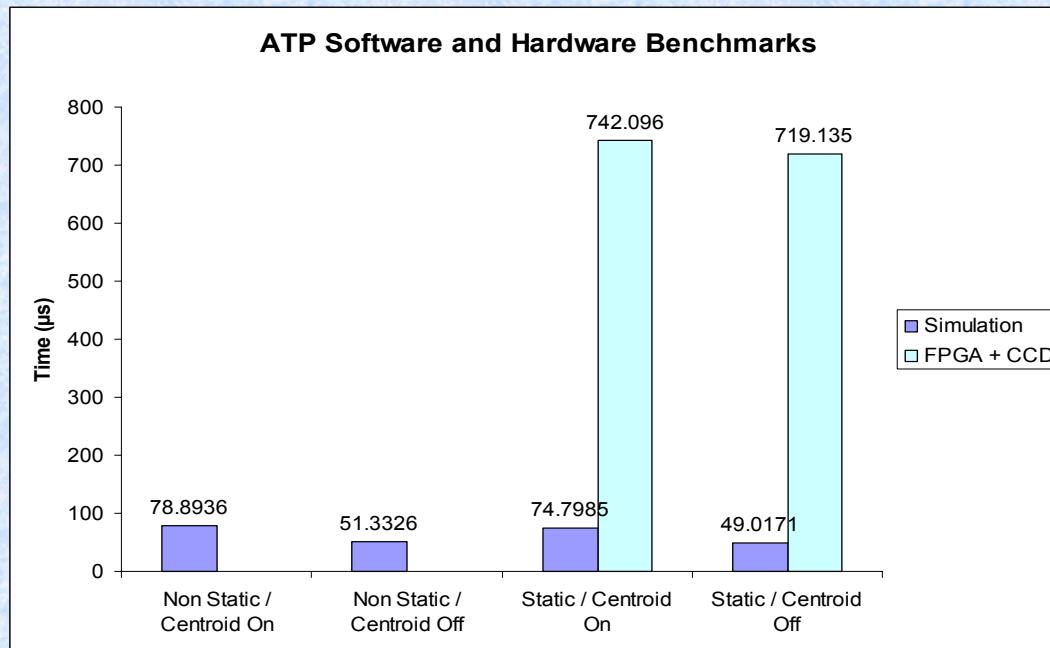
- Characterized RAWCCD Camera
- Demonstrated windowing control logic

Parameter	Present	Target	Datasheet
Read Noise, 1-sigma	160	< 90	12 (slow readout)
Full Well, e-	9100	>22000	30000 typical
CTE	> 0.9995	> 0.9998	> 0.9999
Pixel Nonuniformity	3.5%	2%	15%
Effective Dynamic Range (bits)	5.8	8	11.5 (slow readout)

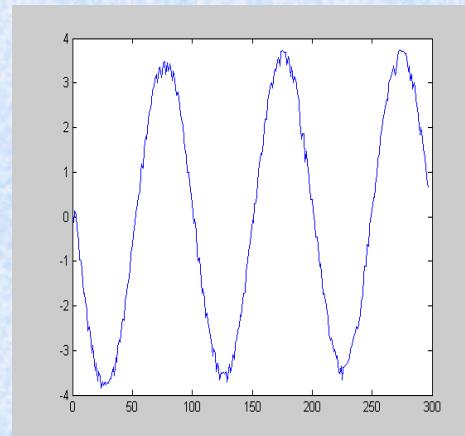


Laboratory Demonstration Progress

- *Integrated TC237 Camera, DCS, ADC/DAC, FSM, Optics, Software*
- *Completed Windowing Algorithm Development*
- *Beam Tracking Demonstrated*



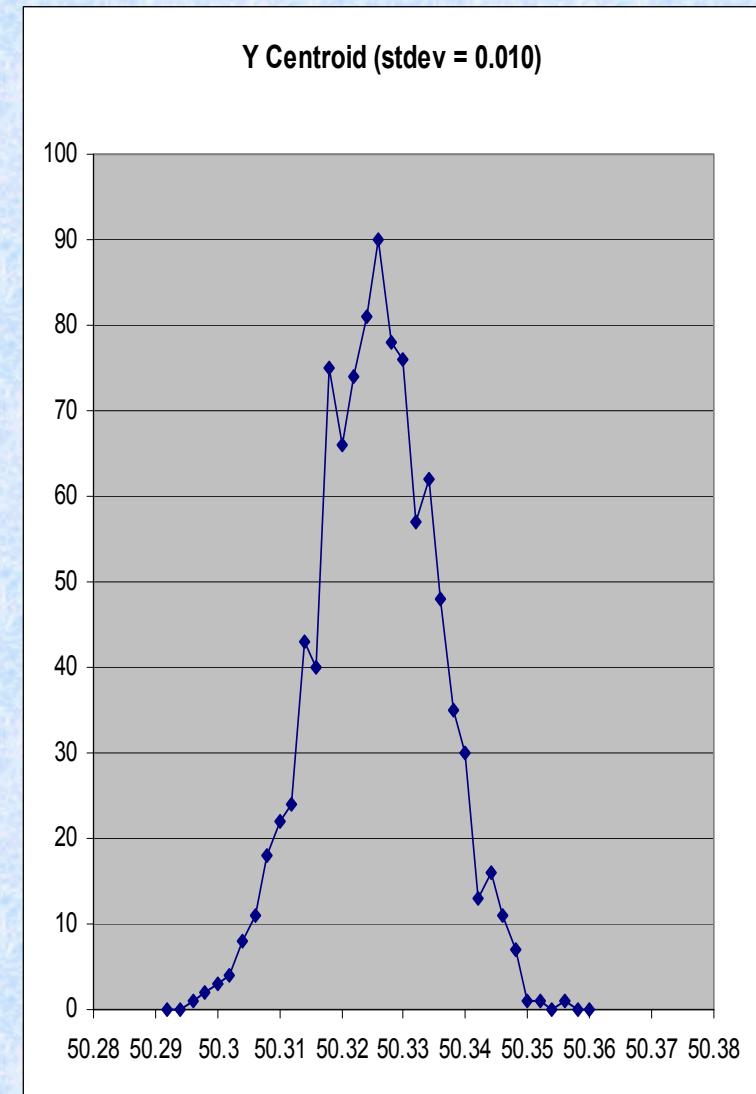
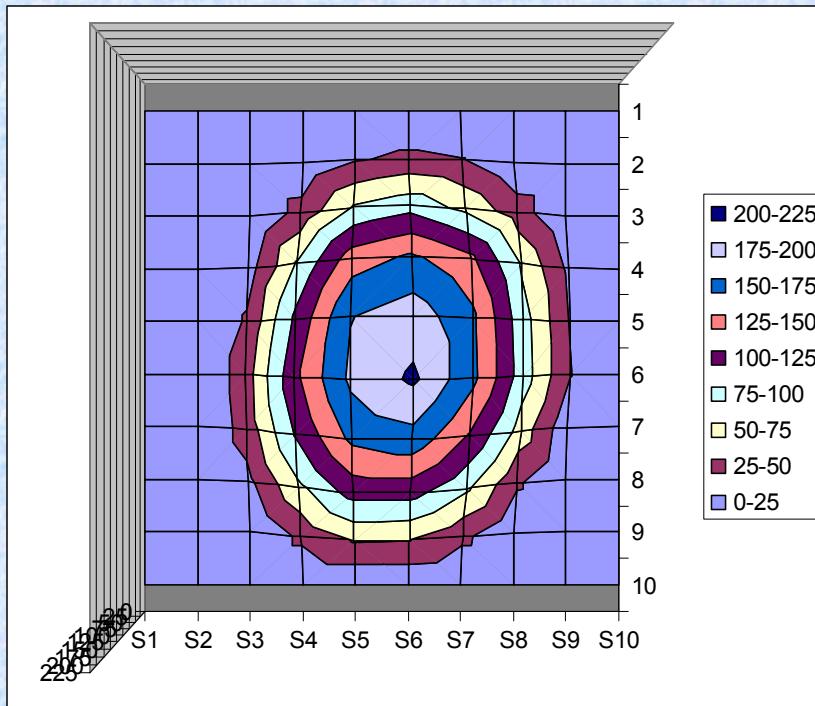
Beacon Spot on TC237 Camera



X Centroid Position over a 300 frame sample (Average is subtracted) in pixels

Laboratory Demonstration Progress

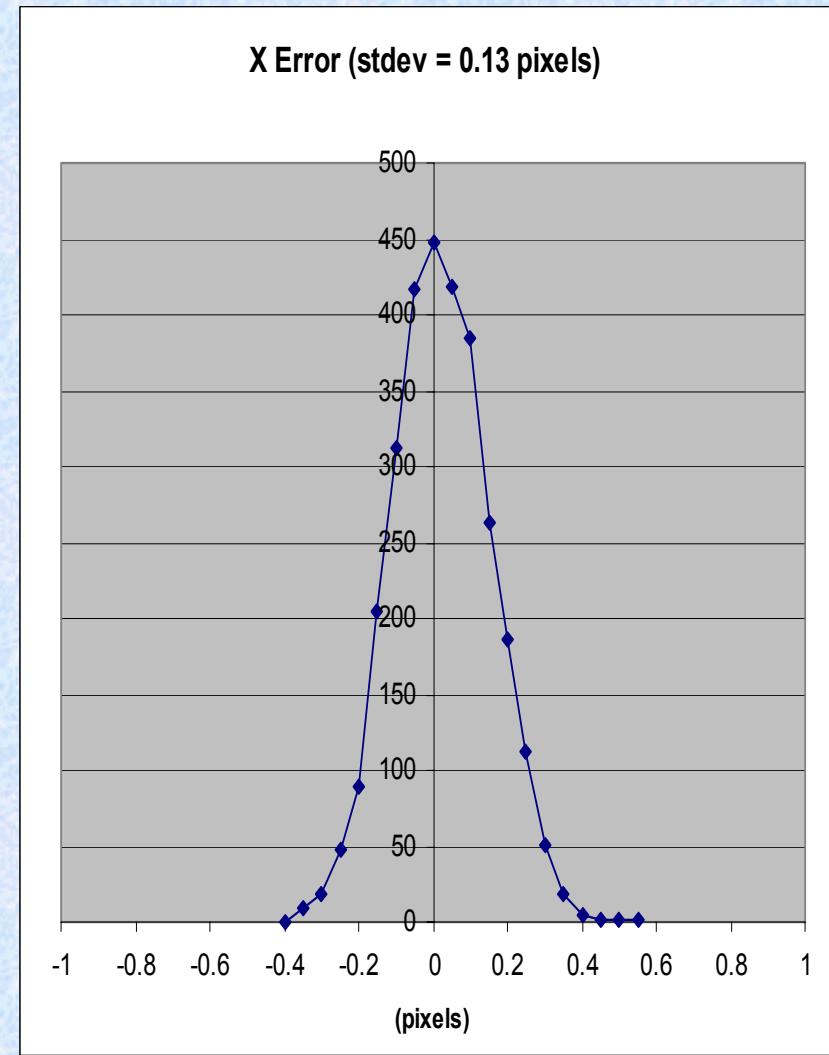
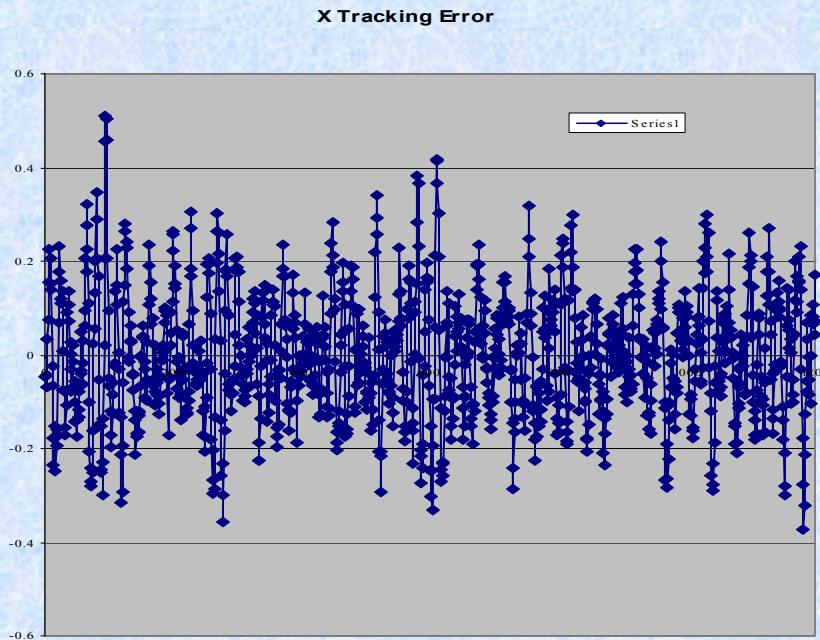
- **0.039 urad (1 sigma)**
 - 3.86 urad/pixel FOV



Measured Tracking Accuracy

Laboratory Demonstration Progress

- **0.50 urad (1 sigma)**
 - 3.86 urad/pixel FOV
 - Vibration jitter $\sim 1/10^{\text{th}}$ of Olympus PSD
 - Update rate @ 600 Hz

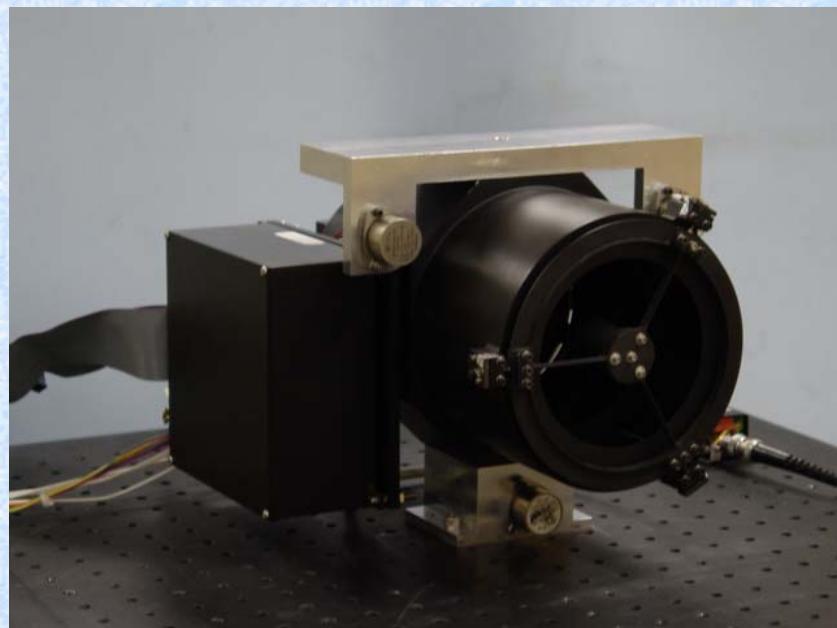


Estimated vs. Measured Performance

Laboratory Demonstration Progress

Deep Space Demo ATP Pointing Error Estimate (8/27/02)

Error Source	Device Parameters			Pointing Jitter (urad)		
	Mars Design Budget	Lab Demo Predicted	Lab Demo Measured	Mars Design Budget	Lab Demo Predicted	Lab Demo Measured
Beacon Sensor Jitter				0.361	0.534	0.534
Noise Equivalent Angle				0.290	0.526	
Centroid window size (odd#, pixels)	5	7	10			
Pixel field of view (urad)	10	3.61	3.61			
Total signal on centroid area (e-)	10k	10k				
Read noise per pixel (e-)	32	100	160			
Dark current per pixel (e-/sec)	TBD	TBD				
Integration Time (ms)	20	20	20			
Sample Rate (kHz)	0.05	0.05	0.05			
FPA full well per pixel (e-)	30k	22k	22k			
ADC effective resolution (bits)	9	8	6			
Spatial quantization				0.200	0.090	
Spot size (pixel)	3.5	6	4.5			
Beam type	Spoiled Airy (Norm1)	Gaussian FWHM@2 pixels				
Pixel QE						
Pixel Non-uniformity				0.080	0.029	
Responsivity variation (%)	2	2	3.5			
Transmit Sensor Jitter				0.107	0.065	0.036
Noise Equivalent Angle				0.050	0.057	
Centroid window size (odd#, pixels)	5	7	10			
Pixel field of view (urad)	10	3.60	3.61			
Total signal on centroid area (e-)	100k	100k				
Read noise per pixel (e-)	32	100	160			
Dark current per pixel (e-/sec)						
Integration Time (ms)	20	20	1.25			
Sample Rate (kHz)	5	5	0.8			
FPA full well per pixel (e-)	30k	22k	22k			
ADC effective resolution (bits)	9	8	6			
Spatial quantization				0.050	0.006	
Spot size (pixel)	?	5	8			
Beam type	Gaussian	Airy 1st min@ 2 pixels				
Pixel QE						
Pixel Non-uniformity				0.080	0.031	
Responsivity variation (%)	2	2	3.5			
Residual PosEst Error				0.520	0.520	0.520
Beacon update rate (Hz)	50					
PosEst Algorithm Accuracy/Noise						
Accelerometer Sample Rate (kHz)	5					
RMS over BW						
Accelerometer accuracy (%)						
Accelerometer resolution (ug)	0.1					
Accelerometer frequency response						
Measured vibration on the breadboard	80ug	<340ug	<340ug			
Filter BW						
# of Accelerometers/Configuration	3	3	3			
Distance between Accel. (cm)						
Residual Tracking Error				0.300	0.650	0.650
Spacecraft Vibration PSD	Cassini-like	Cassini-like	sinusoid			
FSM Command Rate (kHz)	5	5	1.3 kHz			
Rejection Model	OCD 5kHz	OCD 5kHz				
Rejection Bandwidth (Hz)						
Open-Loop BW (Hz)						
Closed-Loop BW (Hz)	500					
TOTAL POINTING JITTER				0.709	0.991	0.990



Sub-microradian ATP Subsystem

predicted value based on vendor parameter specs
predicted value based on best estimated parameter lab performance
predicted valued based on measured parameter lab performance
Measured Lab Parameter

- Developed and analyzed ATP component implementation approaches for sub-microradian pointing throughout the solar system
- Designed, built and integrated advanced Digital Control System
- Built and Integrated Sub-microradian ATP Sub-system Laboratory Breadboard
- Tested RAWCCD Camera performance
- Demonstrated centroiding accuracy to 0.039 urad (1/100th of a pixel)
- Demonstrated fine tracking accuracy to 0.5 urad (1 sigma)
 - With simulated S/C vibration of 1/10th Olympus



Acknowledgement

JPL

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